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Original Article

Balancing for Gross Motor Ability in Exergaming Between Youth with Cerebral Palsy at Gross Motor Function Classification System Levels II and III

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Abstract

Objective: To test how three custom-built balancing algorithms minimize differences in game success, time above 40% heart rate reserve (HRR), and enjoyment between youth with cerebral palsy (CP) who have different gross motor function capabilities. Youth at Gross Motor Function Classification System (GMFCS) level II (unassisted walking) and level III (mobility aids needed for walking) competed in a cycling-based exercise video game that tested three balancing algorithms.

Materials and Methods: Three algorithms: a control (generic-balancing [GB]), a constant non-person specific (One-Speed-For-All [OSFA]), and a person-specific (Target-Cadence [TC]) algorithms were built. In this prospective repeated measures intervention trial with randomized and blinded algorithm assignment, 10 youth with CP aged 10–16 years (X ± standard deviation = 12.4 ± 1.8 years; GMFCS level II $n = 4$, III $n = 6$) played six exergaming sessions using each of the three algorithms. Outcomes included game success as measured by a normalized game score, time above 40% HRR, and enjoyment.

Results: The TC algorithm balanced game success between GMFCS levels similarly to GB ($P = 0.11$) and OSFA ($P = 0.41$). TC showed poorer balancing in time above 40% HRR compared to GB ($P = 0.02$) and OSFA ($P = 0.02$). Enjoyment ratings were high (6.4 ± 0.7/7) and consistent between all algorithms (TC vs. GB: $P = 0.80$ and TC vs. OSFA: $P = 0.19$).

Conclusion: TC shows promise in balancing game success and enjoyment but improvements are needed to balance between GMFCS levels for cardiovascular exercise.

Keywords: Exergames, Fitness, Game mechanisms, Clinical training, Game therapy

Introduction

Cerebral Palsy (CP) is a physical disability associated with decreased motor control.[1] It limits participation in physical activity and cardiovascular exercise.[1,2] Recently, exercise videogames (exergames) have become an appealing option to engage youth in physical activity.[3] Exergames can provide health benefits, including improvement in cardiovascular fitness[4,5] and decreased sedentary screen time.[6] We have developed a suite of exergames, using custom-designed recumbent bicycles connected to an online multiplayer virtual game-world, currently designed for youth with CP at Gross Motor Function Classification System (GMFCS) level III.[7,8] Players cycle on a bicycle to move their avatars in the virtual world and play the mini-games. In our prospective case series of youth at GMFCS level III, we observed improvements in cardiovascular fitness and physical well-being with the exergames.[4,9] However, there is a high degree of variability in gross motor function across the spectrum of CP,[9] and the exergames have not been tested between youth functioning at different GMFCS levels. Youth at GMFCS level II walk unassisted but may have difficulty on uneven surfaces while youth at GMFCS level III require the use of hand-held or wheeled mobility devices.[7] Exergame balancing mechanisms have the potential to address differences in gross motor ability and help all players engage in physical activity, cardiovascular exercise, and have opportunities for game success.[10]

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Traditional game balancing techniques in videogames perform score adjustments to be more lenient for less skilled players.[11] Moderating game success is important as it influences an individual's motivation to play and thus can affect their opportunity for cardiovascular exercise.[12] Players may also have asymmetric roles to encourage group play. In the ''Life is a Village'' game,[13] one player navigates using a recumbent bicycle while the other defends using a controller, allowing players who cannot pedal as quickly to contribute.

''Effort-Based'' balancing, where a player's physiological efforts (i.e., cadence or heart rate [HR]) are used as input to moderate in-game performance, can also facilitate balanced play for people of different abilities. HR has been used to balance in-game performance and improve access to exercise.[8] Stach et al.[10] adjusted in-game performance based on the player's ability to remain in a target HR zone. However, the delay between exercise and exercise-induced changes in HR makes this difficult in fast-paced games.[10] A potential solution may be linking HR to pedaling cadence to serve as a responsive input for ''Effort-Based'' balancing algorithms in cycling-based exergames.

To assess ''Effort-Based'' balancing of different gross motor abilities, we have built three algorithms that use pedaling cadence to moderate avatar speed. In the ''One-Speed-for-All'' (OSFA) algorithm, all avatars move at the same speed as long as the player is pedaling. The OSFA algorithm has facilitated enjoyable exergaming for youth with CP at GMFCS level III.[14] OSFA represents constant, nonperson-specific balancing for game success as it does not require players to pedal at any particular rate; however, there is no explicit motivation to pedal quickly and drive cardiovascular exercise.

In the ''Generic-Balancing'' (GB) algorithm, the players' pedaling cadence directly determines the speed of the avatar, through a logarithmic scale, up to a maximum threshold cadence. GB represents the ''control'' algorithm as it does not specifically address differences in gross motor ability. In typically developing university-aged populations, the GB algorithm has been shown to be enjoyable and elicit cardiovascular exercise, however, may not balance well when there are larger differences in gross motor ability.[15]

The ''Target-Cadence'' (TC) algorithm uses a threshold cadence that was pretested to elicit 40% of each player's heart rate reserve (HRR). The American College of Sports Medicine recommends 20–40 minutes of exercise 3–5 days per week at a minimum of 40% HRR to improve aerobic capacity.[16] At this threshold cadence, avatars move at maximum speed. Unlike the ''Generic-Balancing'' algorithm, where the threshold cadence is the same for all players, the TC algorithm addresses differences in physical ability by setting a unique threshold cadence for each player.

Our primary objective was to test whether the TC algorithm was better able to minimize differences (i.e., balance) in game success, time above 40% HRR, and enjoyment for youth with CP at GMFCS levels II and III compared to the GB and OSFA algorithms. We hypothesized that the TC algorithm would balance game success and enjoyment similarly to OSFA and better than GB. We also hypothesized that the TC algorithm would balance time above 40% HRR better than OSFA but would be similar to GB. The secondary objective was to evaluate how well the predetermined TC matched player's actual in-game cadence while pedaling at 40% HRR.

Materials and Methods

Participants

Participants were a voluntary convenience sample of 10 youth with CP enrolled in a 2-week gross motor camp. Inclusion criteria were 10–16 years of age, GMFCS level II or III, and the ability to operate a hand-held videogame controller. Exclusion criteria were orthopedic surgery in the preceding 3 months of the study, and health conditions including exercise-induced asthma, heart conditions, and uncontrolled seizures.

Study design

This was a prospective repeated measures intervention trial with randomized and blinded algorithm assignment. Thirty minutes of exergaming was an activity on each of the 9 days of camp. The first 2 days were used to calibrate TC goals, followed by six exergame sessions, with one extra day reserved for retesting if participants were unable to attend any session. One of the three balancing algorithms was used for each of the six exergame sessions. To moderate any potential effects of participant improvement during the camp, algorithm order was randomly assigned for the first three sessions and that order was repeated for the last three sessions. Participants and researchers were blind to algorithm order. Ethics approval was granted by Holland Bloorview Kids Rehabilitation and Queen's University's Research Ethics Boards. We engaged in a capacity to consent model and all participants gave written informed consent alongside their caregivers.

Before the camp, participants' maximum and resting/minimum HR were collected. Maximum HR (HR_{max}) was the peak HR achieved during the Shuttle Run Test (SRT), a maximal exercise test validated to assess cardiovascular fitness in children with CP (both GMFCS levels II and III).[17] According to the recommended procedure, participants with GMFCS level II completed the 10 m SRT and participants with GMFCS level III completed the 7.5 m SRT.[17,18] For participants unable to reach 180 beats per minute (bpm), HR_{max} was estimated at 194 bpm, which was found to be the mean HR_{max} of 362 people with CP, 6–19 years old who completed the SRT.[18] Resting HR (HR_{rest}) was set as the minimum HR within 5 minutes upon awakening. All HR data were collected using Polar H1 chest mounted sensors (Polar Electro, Oulu, Finland). Target HR was calculated as $40\% \times (HR_{max} - HR_{rest}) + HR_{rest}$.[17] The threshold of 40% HRR was used in all of the algorithms for in-game incentives (i.e., weapons upgrades).

Cadence testing protocol

On each of the first 2 days, players completed the Cadence Testing Protocol to determine the TC expected to elicit 40% HRR. Participants pedaled at a self-identified rate guided by a metronome, with no avatar displayed. Participants identified a resistance at which they were able to pedal comfortably for 20 minutes. Every 2 minutes, HR was assessed and the metronome tempo was changed such that participants increased or decreased their cadence until reaching 40% HRR ±3 bpm. When they maintained this consistently for 2–5 minutes, the test was complete.[19] TC was the average cadence calculated from each instant the participants pedaled at

40% HRR ±3 bpm. Avatars went at maximum speed when participants pedaled at or above the TC. The participants identified a resistance level to be used for all remaining exergaming sessions to avoid introducing resistance as a confounding variable.

Exergame sessions/interventions

Exergaming sessions were completed in groups of five, with a minimum of two participants at each GMFCS level per group. HR, cadence, and gaming data were recorded continuously during each session. Participants wore a Polar H1 HR monitor while sitting at an exergaming station with a specialized seat equipped with a seatbelt and lateral supports connected to a PCGamerBike Mini (3D Innovations, Greeley, CO) and a Toshiba DX730 computer (Fig. 1).

Three custom-developed mini-games (Wiskin Defense, Biri Brawl, and Gekku Race) were played on each day, in the same order, for 10 minutes each, with 2–5 minutes of rest between mini-games. Participants completed questionnaires between mini-games.

Wiskin Defense is a collaborative game where players gain points by cooperating to defend the ''wiskins'' by combating cat-zombies. In Biri Brawl, players compete by damaging each other to accumulate points. In these games, players pedal consistently to track and defeat their opponent. Accordingly, their game success score depends on how many opponents they move toward and successfully attack.

In Gekku Race, players pedal in quick 30–60 seconds races to be the first up the wall. Here, game success score depends on the player's position in the race, where the player in first place will have the highest game success score. Players see their success in the form of coins. Depending on the mini-game, players receive coins for defeating opponents or for winning the race. Additionally, the winner of the round is announced on-screen at the end of each game, thereby providing feedback about their performance. In the mini-games, the player's avatar moves in response to cycling.[15] Hand-held videogame controllers used a single joystick and button to reduce fine motor demands.[7]

Outcome measures

Three measures were used to address the primary objective. First, game success, defined as the overall score a participant achieved relative to every other player, was calculated from each mini-game and grouped together to produce players' overall game score for each algorithm. Scores were normalized by dividing each player's score by the highest score throughout the study, and described as a percentage of that high score. Normalized game scores were the average across all rounds of all mini-games. Similar scores between players indicate a closer, more balanced game.

Second, for each algorithm, the percentage of playtime above 40% HRR was calculated as follows: total playtime

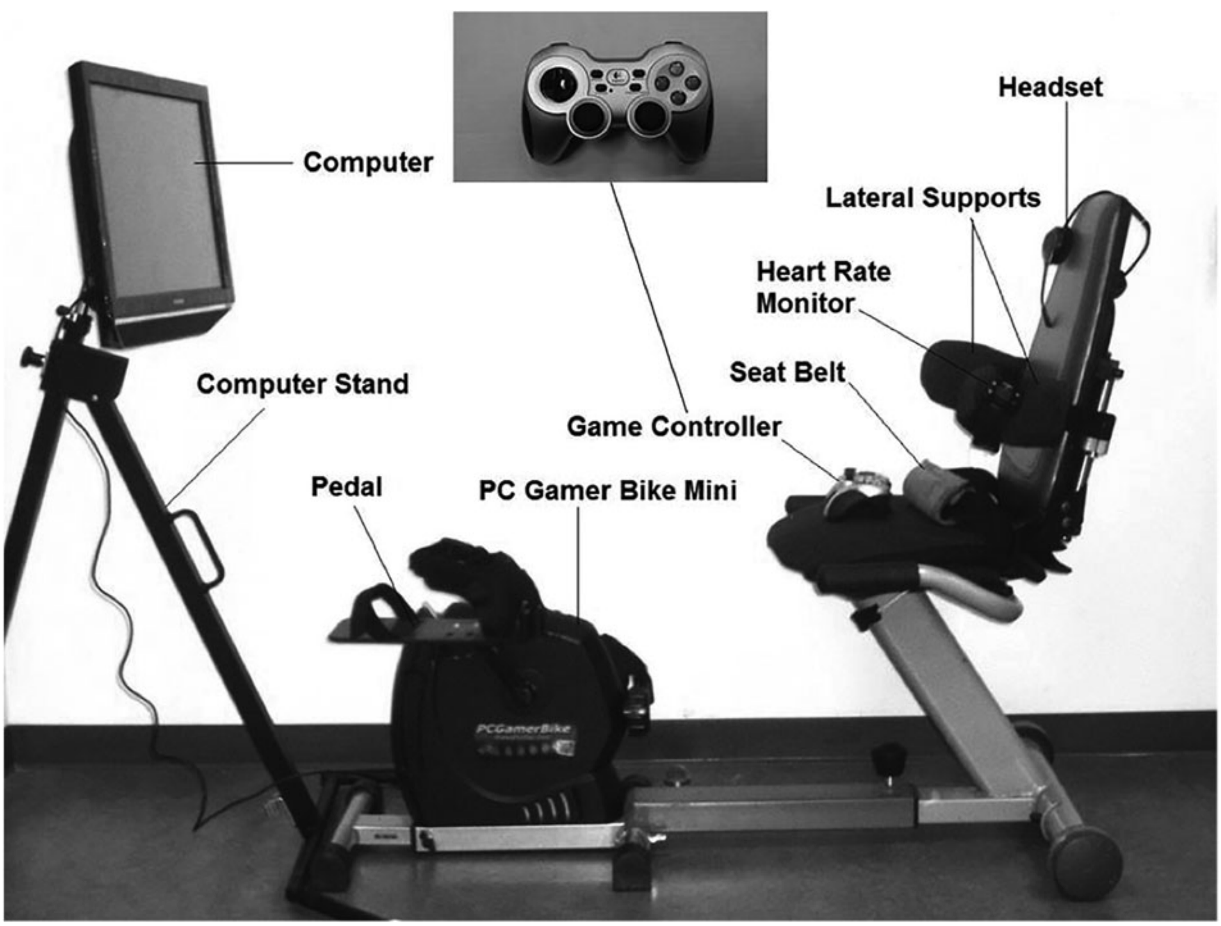

FIG. 1. The exergaming station with Game Controller insert.

above 40% HRR divided by total playtime. Third, player enjoyment was measured using the interest/enjoyment subscale of the nine-point Intrinsic Motivation Inventory (IMI) questionnaire. The IMI questionnaire has been used with youth with CP aged 8–17 years [20] and the interest/enjoyment subscale has demonstrated construct validity as a reliable measure for assessing subjective experience during physical activity ($\alpha = 0.78$).[21] The interest/enjoyment subscale was completed after each mini-game. The median score from each mini-game was then grouped by algorithm.

To evaluate the secondary objective of how well the predetermined TC matched actual game cadence while working at 40% HRR ±3 bpm, the average difference between TC and game cadence was calculated across algorithms. Game cadence is the player's actual pedaling cadence while they were working at 40% HRR ±3 bpm.

Statistical analyses

Descriptive statistics were calculated for outcome variables and participant characteristics. Univariate analyses were conducted for both independent variables (algorithms and GMFCS level) on game success, percentage of time above 40% HRR, and enjoyment. To address our primary objective, four separate two-way repeated measures mixed analyses of variance (ANOVAs) examined the effects of algorithm (TC vs. GB and TC vs. OSFA) and GMFCS (level II vs. III) on the dependent variables: normalized game success and percent of time above 40% HRR. Bonferroni adjustments were used to account for multiple comparisons.

Following statistically significant results, post hoc comparisons between GMFCS levels for each algorithm were examined. The aligned rank transform (ART) method was applied to IMI interest/enjoyment scores and two mixed ANOVAs were performed.[22] Following any significant results, Wilcoxon Signed Rank tests were used to identify post hoc differences in GMFCS levels for each algorithm. For our secondary analysis, a repeated measures ANOVA evaluated how well predetermined TC matched actual game cadence while working at 40% HRR ±3 bpm.

Results

Demographic information

Ten youth (5 female; $\overline{X}$ age = 12.4 ± 1.8 years) participated, nine with bilateral spastic diplegia and one with mixed (spastic diplegia and dyskinesia) CP. Four participants were classified as GMFCS level II ($\overline{X}$ age = 14.0 ± 1.9 years). Six were classified as GMFCS level III ($\overline{X}$ age = 12.3 ± 1.5 years). Eight participants were at Manual Abilities Classification System level I, and two at level II.[23] We did not find differences in age or gender to be associated with game success, percent of time above 40% HRR, or enjoyment outcomes.

Game success

The average normalized game success score for all participants was 66.0% ± 8.1%. When comparing TC and GB algorithms, game success was 6.6% higher with TC (70.2% ± 5.2%) than with GB (62.6% ± 8.9%) ($P = 0.01$); and 9.9% higher for GMFCS level II (72.3% ± 5.9%) than level III (62.4% ± 7.1%) ($P = 0.01$). When comparing TC and OSFA, game success was 4.9% higher with TC (65.3% ± 6.7%) ($P = 0.03$) and 8.1% higher for GMFCS level II (72.5% ± 5.1%) than level III (64.4% ± 6.8%) ($P = 0.04$). Toward our primary objective, the mixed ANOVA showed no significant interaction between GMFCS level and algorithm for both TC versus GB ($F_{1,8} = 3.2$, $P = 0.11$) and TC versus OSFA ($F_{1,8} = 0.74$, $P = 0.41$) (Fig. 2).

Percent of time above 40% HRR

Of the total 189 minutes, participants spent an average of 53.3% ± 32.5% of time above 40% HRR. Time above 40% HRR was similar between TC (54.6% ± 34.7%) and GB algorithms (52.4% ± 31.1%) ($P = 0.18$) and between TC and OSFA algorithms (52.7% ± 31.6%) ($P = 0.25$). Comparing TC and GB, participants at GMFCS level II spent 65.9% ± 22.0% of time above 40% HRR whereas participants at GMFCS level III spent 45.3% ± 33.9% of time above 40% HRR ($P = 0.36$). Similarly, comparing TC and OSFA, participants at GMFCS

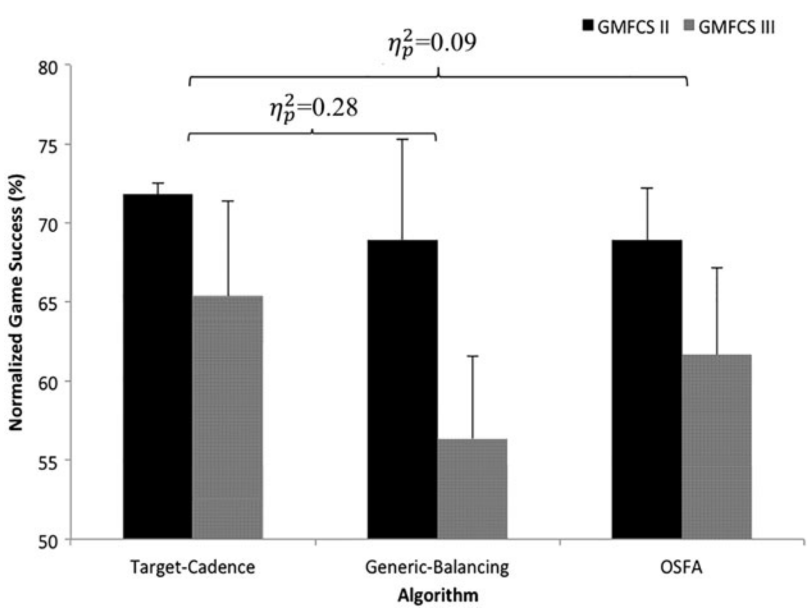

FIG. 2. Normalized game success by algorithm and GMFCS. GMFCS, Gross Motor Function Classification System; OSFA, One-Speed-For-All.

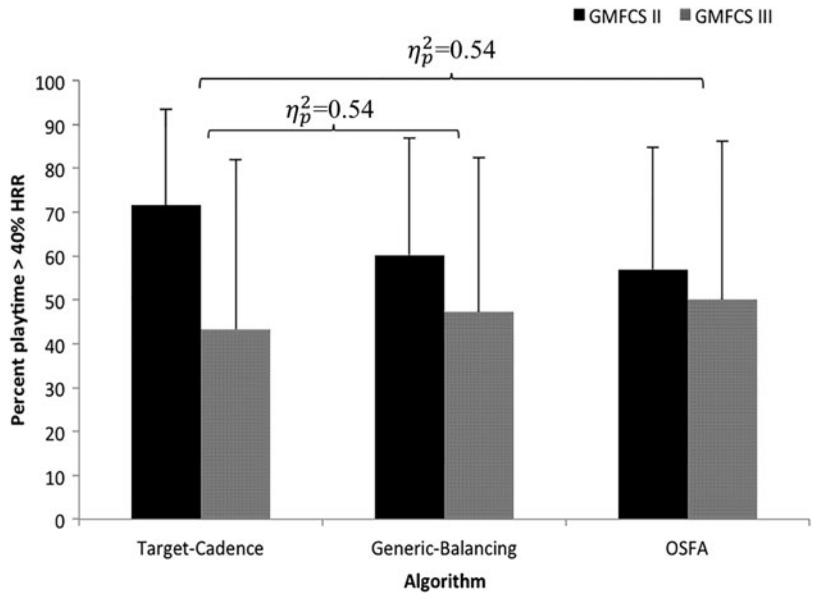

FIG. 3. Percent of time spent playing above 40% heart rate reserve by GMFCS and algorithm.

level II spent 64.4% ± 23.0% time above 40% HRR, 11.4% more than those at level III (53.0% ± 33.8%) ($P = 0.42$). Toward our primary objective, the mixed ANOVA showed a significant effect between GMFCS level and algorithm for both TC versus GB ($F_{1,8} = 8.1$, $P = 0.02$) and TC versus OSFA ($F_{1,8} = 9.0$, $P = 0.02$) (Fig. 3). Following this result, no significant post hoc differences were found between GMFCS levels for any one algorithm (TC $P = 0.22$, GB $P = 0.55$, OSFA $P = 0.78$).

Enjoyment

Overall, mean interest/enjoyment score from the IMI was 6.4 ± 0.7 out of 7. IMI interest/enjoyment scores were similar between TC (6.5 ± 0.6) and GB (6.4 ± 0.7) ($P = 0.68$) algorithms and between TC and OSFA algorithms (6.3 ± 0.8) ($P = 0.15$). When comparing TC and GB algorithms, participants at GMFCS level II scored 6.3 ± 0.7 while participants at GMFCS level III scored 6.5 ± 0.6 ($P = 0.83$). Between TC and OSFA algorithms, participants at GMFCS level II scored 6.2 ± 0.7 while participants at level III scored and 6.5 ± 0.6 ($P = 0.62$). Toward our primary objective, enjoyment scores with the TC algorithm between participants at GMFCS levels II and III were balanced similarly to GB ($F_{1,8} = 0.06$, $P = 0.80$) and OSFA algorithms ($F_{1,8} = 1.7$, $P = 0.19$) (Fig. 4).

TC and game cadence

Participants' TC averaged 59.5 ± 10.3 revolutions per minute (rpm) for participants at GMFCS level II and 44.8 ± 13.6 rpm for participants at GMFCS level III. Actual game cadence when working at 40% HRR ±3 bpm was 51.9 ± 5.7 and 38.8 ± 9.0 rpm for participants at levels II and III respectively. TC was significantly higher than game cadence, regardless of GMFCS level ($F_{2,8} = 8.62$, $P = 0.02$).

Discussion

This research evaluated how well the TC algorithm balanced for differences in gross motor abilities of youth with CP at GMFCS levels II and III as measured by game success, cardiovascular exercise, and enjoyment. Trends toward the best balance (i.e., minimizing differences between players at

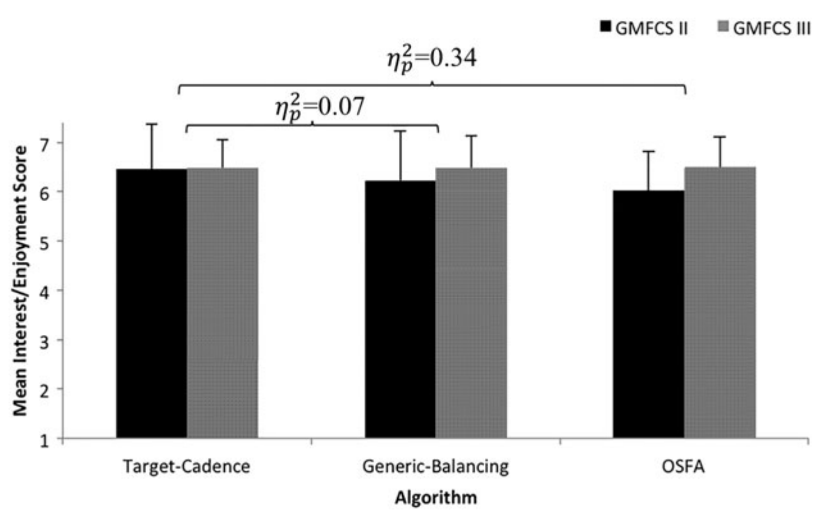

FIG. 4. Interest/enjoyment scores by algorithm and GMFCS.

GMFCS levels II and III) was seen with the TC algorithm for game success and enjoyment. However, the TC algorithm showed the poorest balancing in time above 40% HRR between players at GMFCS levels II and III. While all participants enjoyed the exergames, participants at GMFCS level II had greater game success and spent more time above 40% HRR than participants at level III. These differences highlight the need for continued refinement of balancing for gross motor abilities in exergaming for youth with CP.

Being successful while exergaming can be motivating and increase opportunities for cardiovascular exercise and social engagement.[13] As such, it is important to minimize differences in game success between participants with different gross motor abilities. The TC algorithm addressed differences in ability by setting the participants TC relative to their cadence at 40% HRR, whereas in GB and OSFA there is no participant-specific consideration. Accordingly, the TC algorithm showed the smallest differences in game success across all participants. However, participants at GMFCS level II were still more successful. This indicates that balancing exergames based on individual ability is promising but further refinement is necessary to ensure that participants with higher gross motor function are not inherently more successful.

From a cardiovascular fitness perspective, participants exercised more than half the time (101 of 189 minutes) above 40% HRR, indicating that these exergames provided an outlet for moderate intensity aerobic activity.[16] However, participants at GMFCS level II spent more time above 40% HRR across all algorithms than participants at GMFCS level III. Counter to our hypothesis, the TC algorithm showed worse balancing between players in GMFCS levels II and III compared to both GB and OSFA. The TC algorithm requires participants to pedal at a predetermined TC expected to elicit 40% HRR to achieve maximum game speed. However, the predetermined TC was higher than the actual game cadence while exergaming at 40% HRR for all participants. This was likely due to the difference between pedaling styles during gameplay and cadence testing.

During gameplay, participants frequently pedaled in bursts. Pedaling fluctuations could have led to an overall lower average cadence in the game, as compared to the constant pedaling rate in the cadence test. This means participants had to work harder than expected to reach maximum game speed, which could have compromised the effectiveness of the TC algorithm, especially for participants at GMFCS level III. Compared to players at GMFCS level III, players at GMFCS level II are able to pedal faster for long, and therefore reach and maintain these artificially high TC goals.[24] It is important to ensure that the predetermined TC accurately reflects an individual's ability during actual gameplay.

Activity choices can be highly directed by enjoyment.[3] Enjoyment can impact self-efficacy, direct motivation, and adherence to exercise interventions. Therefore, it is critical to ensure exergame play is consistently enjoyable to all participants regardless of ability.[12,25] All participants, regardless of GMFCS level highly enjoyed the exergames during the camp. However, counter to our hypothesis, enjoyment ratings were similar between GMFCS levels across all algorithms. Overall, the exergames are enjoyable, promotes moderate intensity exercise, and can be considered an important component of the rehabilitation tool kit, potentially helping to sustain participation over time.[4,26,27]

It is important to acknowledge potential limitations to our study. First, our results may be underpowered due to the small sample size. Second, success is not solely based on gross motor ability. Success relies on an interaction of factors including: visual-spatial coordination, gaming skill, motivation, and attention, which were not controlled for here.

Age and gender may also influence how individuals interact within the gaming environment and should be considered as potential confounding variables. Given the number of groups and conditions, it was not possible to have a completely balanced algorithm assignment with respect to minimizing a potential order effect of algorithm play. However, the algorithms were equally distributed between groups and sessions and thus order of play should have had a minimal impact on the results in this study. The algorithm effectiveness may have also been confounded by the social support and encouragement participants received from camp staff.

Our results show how balancing mechanisms can facilitate exergaming success, fitness, and enjoyment between youth with different physical abilities but refinement is necessary to motivate participants to pedal as quickly as they are able to while providing opportunities for game success. We expect a more effective balancing mechanism should directly reflect the individual's physical ability.

One method could use participants' Gross Motor Function Measure (GMFM) score to help determine TC goals. The GMFM is a Rasch derived scale measuring gross motor function/ability of individuals with CP across all GMFCS levels and may be beneficial for setting TC goals as it has a standardized outcome measure ranging from 0 to 100.[28] Setting TC goals based on GMFM scores may facilitate cardiovascular exercise by better allowing players across different abilities to be competitive with each other.

With continued refinement and evaluation of balancing algorithms, we aim to foster inclusive gaming that facilitates cardiovascular exercise and social engagement for people with different abilities.

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Author Disclosure Statement

No competing financial interests exist.

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